GP-302602

IMPROVED FLUX OBSERVER IN A SENSORLESS CONTROLLER FOR PERMANENT MAGNET MOTORS

FIELD OF THE INVENTION

[0001] The present invention relates to electric machines, and more particularly to sensorless rotor position estimation for electric machines.

BACKGROUND OF THE INVENTION

[0002] Open-loop flux observers are used to estimate rotor position in an electric machine such as a permanent magnet (PM) motor. The open-loop flux observer is typically called a "sensorless" estimator because the rotor position is inferred rather than measured directly. Direct rotor position sensors typically include rotor position transducers (RPTs) or other sensors that sense movement of the rotor. Direct rotor position sensors are typically costly to implement and may tend to reduce the reliability of the electric machine.

[0003] The open-loop flux observer estimates rotor position using stator currents and commanded stator voltages as inputs. The open-loop flux observer calculates the back EMF of the electric machine. There are several characteristic equations that are used:

$$\Psi_{dqs}^{s} = \int \left(V_{dqs}^{s*} - R_s \cdot i_{dqs}^{s} \right) dt \qquad (1)$$

$$\theta_{\Psi_s} = \tan^{-1}\left(\frac{\Psi_{qs}^{s}}{\Psi_{ds}^{s}} \right) \qquad (2)$$

$$\delta = \tan^{-1}\left(\frac{\Psi_{qs}^{e}}{\Psi_{ds}^{e}} \right) = \tan^{-1}\left(\frac{L_q \cdot i_{qs}^{e}}{\Psi_f + L_d \cdot i_{ds}^{e}} \right) \qquad (3)$$

$$\theta_r = \theta_{\Psi_s} - \delta \qquad (4)$$

Where Ψ_{dqs}^{s} is the stator flux linkage in the stationary reference frame, i_{dqs}^{s} is the stator current in the stationary reference frame, R_s is the stator resistance, Ψ_{ds}^{s} and Ψ_{qs}^{s} are the d-axis and q-axis stator flux linkages in the stationary reference frame, Ψ_{ds}^{e} and Ψ_{qs}^{e} are the d-axis and q-axis stator flux linkages in the stationary reference frame, Ψ_f is the permanent magnet flux linkage, L_d is the d-axis inductance, L_q is the q-axis inductance, i_{ds}^{e} and i_{qs}^{e} are synchronous reference frame currents, θ_r is the rotor position, θ_{Ψ_s} is the angular position of the stator flux and δ is the load angular position.

[0004] The back EMF is integrated to obtain the stator flux linkage in a stationary reference frame (See Equation 1). The angular position of the stator flux is usually obtained using the arctangent function (See Equation 2). The rotor position information is obtained by subtracting the load angular position δ (See Equation 3) from the stator flux position (See Equation 4).

[0005] In most implementations, however, an integration function that is set forth in Equation 1 is not used. Cascaded low pass filters (LPF) are typically used to simulate the integration function to avoid integration problems that occur at low stator frequencies. Cascaded LPFs also provide improved transient response as compared to a single LPF since faster time constants can be used.

[0006] The conventional open-loop flux observer has several performance problems. The cascaded LPFs require electrical speed data, which is not normally available from basic open-loop observers. The electrical speed data is used to set the LPF coefficients. To generate the electrical speed data, a derivative of angular position is generated. The derivative operation tends to be noise sensitive and can create errors in the electrical speed data. The electrical speed data is used to compute the coefficients of the cascade LPFs. Errors in

the electrical speed data adversely impact LPF characteristics such as gain and phase and may cause instability. Also, the conventional open-loop flux observer requires an arctangent function, which can be computationally intensive.

SUMMARY OF THE INVENTION

[0007] A control system includes a field oriented controller that receives a torque command and that generates phase voltages for an electric machine including a rotor and a stator. A first transformation module receives stator terminal currents and generates d-axis and q-axis stationary frame currents. An open loop flux observer receives d-axis and q-axis stationary frame voltage commands and the d and q-axis stationary frame currents. The open loop flux observer includes a vector cross product calculator that generates an error signal that is proportional to an angular difference between an estimated stator flux and a computed stator flux and a proportional integral controller that generates an estimated rotor angular position based on the error signal. A second transformation module receives the d-axis and q-axis stationary frame currents, and the estimated rotor angular position and generates d-axis and q-axis synchronous reference frame feedback currents that are output to the field oriented controller.

[0008] In other features, the electric machine is a permanent magnet electric machine. The open loop flux observer includes a d-axis voltage drop calculator that calculates a d-axis stator voltage drop due to stator resistance. A q-axis voltage drop calculator calculates a q-axis stator voltage drop due to the stator resistance. A first summer generates a d-axis back EMF by calculating a first difference between the d-axis stationary frame voltage command and the d-axis stator voltage drop. A second summer generates a q-axis back EMF by

calculating a second difference between the q-axis stationary frame voltage command and the q-axis voltage drop.

[0009] In still other features, the open loop flux observer includes a first low pass filter that receives an electrical angular velocity estimate and the d-axis back EMF and that generates a d-axis stator flux linkage value. A second low pass filter receives the electrical angular velocity estimate and the q-axis back EMF and generates a q-axis stator flux linkage value.

[0010] In yet other features, the vector cross product calculator includes a sine function generator that generates a sine value of an estimated stator flux angular position. A cosine function generator generates a cosine value of the estimated stator flux angular position. A first multiplier multiplies the sine value by the d-axis stator flux value. A second multiplier multiplies the cosine value by the q-axis stator flux value. A first difference circuit generates an error signal that is based on a difference between the two products, which is also the cross product.

[0011] In other features, the open loop flux observer further includes a load angular position circuit that generates a load angular position. A derivative calculator calculates a derivative of the load angular position. A summing circuit generates a stator flux angular velocity by summing the load angular position derivative and the estimated electrical angular velocity. An integrator integrates the stator flux angular velocity to generate a stator flux position. A second difference circuit generates the estimated angular rotor position based on a difference between the stator flux position and the load angular position.

[0012] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the

invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0014] FIG. 1 is a functional block diagram of an open-loop flux observer circuit according to the present invention and a sensorless drive circuit;

[0015] FIG. 2 is a more detailed functional block diagram of the open-loop observer of FIG. 1;

[0016] FIG. 3 is a plot illustrating d-axis and q-axis back EMF voltages;

[0017] FIG. 4 is a plot illustrating the transient torque response without a feedforward term;

[0018] FIG. 5 is a plot illustrating the transient torque response with a feedforward term according to the present invention;

[0019] FIG. 6 is a plot illustrating transient performance during forward acceleration; and

[0020] FIG. 7 is a plot illustrating transient performance during reverse acceleration.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] The following description of the preferred embodiment(s) is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify the same elements.

[0022] The present invention eliminates several problems that are associated with conventional open-loop flux observers. In particular, the present invention replaces the arctangent function using

a vector cross product (VCP) error function and a proportional integral (PI) controller. The open-loop flux observer circuit according to the present invention provides smooth speed estimation data that can be used by the cascade LPFs. Correct system dynamics are maintained by including a derivative of load angular position (dδ/dt) feedforward term in the open-loop flux observer.

[0023] Referring now to FIG. 1, an open-loop flux observer circuit 10 according to the present invention is applied to a sensorless driver for an IPM machine 14 such as a motor or a generator. A field-oriented controller 18 receives a torque command Te* and synchronous reference frame feedback currents I_{ds}^{e} and I_{qs}^{e}. The field-oriented controller 18 generates actual phase voltages 22 that are applied to inputs of the IPM machine 14.

[0024] Motor phase or stator terminal currents are measured and processed by a 3-phase to 2-phase transformation module 30. The outputs of the transformation module 30 are the stationary frame currents I_{ds}^{s} and I_{qs}^{s}. The open-loop flux observer circuit 10 generates an estimated rotor angular position θ_r and angular speed w_r. A stationary to rotating frame transformation module 34 uses the estimated rotor angular position θ_r to generate synchronous reference frame feedback currents I_{ds}^{e} and I_{qs}^{e}. The synchronous reference frame feedback currents I_{ds}^{e} and I_{qs}^{e} are output to the field-oriented controller module 18.

[0025] The open-loop flux observer circuit 10 processes the stationary frame currents I_{ds}^{s} and I_{qs}^{s} and stationary frame voltage commands V_{ds}^{s*} and V_{qs}^{s*} to generate the estimated rotor angular position θ_r and estimated rotor angular velocity ω_e. Note that in a synchronous machine, $\omega_e = \omega_r$.

[0026] Referring now to FIG. 2, a detailed block diagram of the open-loop flux observer circuit 10 is shown. Stationary frame current I_{ds}^{s} is multiplied by the stator resistance R_s using gain block 50 to compute a d-axis stator resistance voltage drop. The output of gain block 50 is subtracted from the d-axis stator voltage command V_{ds}^{s*} using a summer 54. The output of summer 54 is the d-axis back-EMF e_{ds}^{s}. The d-axis back-EMF is output to cascade LPFs 60, which use the electrical angular velocity ω_e to determine the appropriate coefficients for the cascade LPFs 60. The cascade LPFs 60 integrate the d-axis back-EMF to obtain the d-axis stator flux linkage Ψ_{ds}^{s}.

[0027] Stationary frame current I_{qs}^{s} is multiplied by the stator resistance using gain block 70 to compute the q-axis stator resistance voltage drop. The output of gain block 70 is subtracted from the q-axis stator voltage command V_{qs}^{s*} using a summer 74. The output of summer 74 is the q-axis back EMF e_{qs}^{s}. The q-axis back EMF is passed to cascade LPFs 80, which use the electrical angular velocity ω_e to determine the appropriate coefficients for the cascade LPFs 80. The cascade LPFs 80 integrate the q-axis back EMF to obtain the q-axis stator flux linkage Ψ_{qs}^{s}.

[0028] A vector cross product calculator 84 calculates a vector cross product between the observer estimated stator flux angular position unit vector and the computed stator flux vector. Block 86 computes the sine of the estimated stator flux angular position θ_{Ψ_s}. Block 88 computes the cosine of the estimated stator flux angular position θ_{Ψ_s}. Multiplier 90 generates a product of the computed d-axis stator flux and the sine of the estimated stator flux angular position. Multiplier 92 generates a product of the computed q-axis stator flux and the cosine of the estimated stator flux angular position. Summing

junction 94 subtracts the output of block (13) from the output of block (12) to generate the error signal ε.

[0029] The error signal ε is proportional to the angular position difference between the estimated stator flux angular position unit vector and the computed stator flux vector as can be seen in seen Equation 5 below:

$$\begin{aligned} \varepsilon &= (\cos\theta_{\Psi s} + j\sin\theta_{\Psi s}) \times \overrightarrow{\Psi}_{dqs} = |\Psi_s| \sin\theta_{error} \\ \varepsilon &\approx |\Psi_s| \cdot \theta_{error} \end{aligned} \qquad (5)$$

Error signal ε is input to anti-windup PI controller 100, whose output is ω_{e_raw}. The anti-windup PI controller 100 functions such that θ_{error} goes to zero. ω_{e_raw} is passed through low pass filter 104 to produce the estimated electrical angular velocity ω_e. This signal is also passed to cascade LPFs 60 and 80.

[0030] During load transients, the stator flux angular velocity does not equal the electrical angular velocity as can be seen in Equation 6 below:

$$\omega_{\Psi s} = \omega_e + \frac{d\delta}{dt} \qquad (6)$$

The dδ/dt term can be used in feedforward manner in the open-loop flux observer to improve the torque transient response. The load angular position δ is passed by a load angular position calculator 110 to a derivative generator 112. The output of derivative generator 112 is passed through low pass filter 116 to remove unwanted high frequency noise created by the derivative. The output of LPF 116 is scaled with gain block 120. The output of gain block 120 is summed with the output of the anti wind-up PI 100 via summing junction 124 to produce $\omega_{\Psi s}$, which is fed to integrator 128, which outputs the estimated stator flux position $\theta_{\Psi s}$. The load angular position δ is calculated by block 110 based on Equation 3 and subtracted from the

stator flux position using summing junction 130 to obtain the final rotor position θ_r (see Equation 4).

[0031] The present invention was implemented and tested in the laboratory using a 75kW interior permanent magnet motor. Figure 3 shows the d-axis and q-axis back EMF voltages e^s_{dqs} and resultant computed d and q-axis stator fluxes Ψ^s_{dqs} as calculated by the cascade LPFs. In FIG. 3, n_r = 500rpm and T=50Nm. The 90° of phase-shift introduced by the integration can be seen in the FIG. 3. The high frequency ripple on e^s_{dqs} is inherent in the design of this IPM motor and is effectively filtered out during the integration process at this speed.

[0032] Referring now to FIG. 4, the torque transient response of the open-loop flux observer shown in FIG. 2 with K_δ=0 (no dδ/dt feedforward term). In FIG. 4, rotor speed n_r = 500rpm and $T^* = 0 \rightarrow$ 50Nm at 3600Nm/s. A step in ω_{e_est} occurs, which should be constant. The dynamometer held the speed constant during the torque transient test. As can be seen in the FIG. 4, the estimated electrical speed has a large transient. In reality, the actual rotor speed was held constant, therefore the observer generated the error in the estimated electrical speed.

[0033] In FIG. 5, the test was repeated with K_δ=1 (added dδ/dt feedforward term per the present invention), a constant rotor speed n_r = 500rpm, and $T^* = 0 \rightarrow$ 50Nm at 3600Nm/s. Notice ω_{e_est} is now constant due to the dδ/dt feedforward term. $\omega_{\Psi s\_est}$ has a temporary increase during torque transients, as explained by Equation 6.

[0034] In this case, it can be seen that the estimated electrical speed is constant. The estimated stator flux speed has a transient due to the dδ/dt caused by changing load angular position

(see Equation 6). These two figures clearly demonstrate the effectiveness of the present invention during torque transient.

[0035] Speed transient performance of the proposed open-loop flux observer is shown in FIGs. 6 and 7. FIG. 6 shows the forward direction acceleration with +180Nm (100%) torque command (forward motoring), $N_r = 500 \rightarrow 5000$rpm at 2000rpm/sec acceleration rate, and T = +180Nm. Torque is reduced at high speed due to field weakening. As speed increases, the torque is decreased due to field weakening operation of the control in the constant power region.

[0036] FIG. 7 shows the reverse direction acceleration with -180Nm (-100%) torque command (reverse motoring), $N_r = -500 \rightarrow -5000$rpm at 2000rpm/sec acceleration rate, and T = -180Nm. Torque is reduced at high speed due to field weakening. From FIGs. 6 and 7, excellent performance of the open-loop flux observer according to the present invention is demonstrated.

[0037] Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the present invention can be implemented in a variety of forms. Therefore, while this invention has been described in connection with particular examples thereof, the true scope of the invention should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification and the following claims.